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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Free electron lasers with short Rayleigh length

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Abstract

To decrease power loading on cavity mirrors, a Gaussian mode with a very short Rayleigh length could be employed. We study the physics of the FEL interaction while shortening the Rayleigh length in the FEL oscillator. The results can be applied to the Industrial Laser Consortium's UV FEL and to high average power FELs in general.

High power density on cavity mirrors is a problem shared by ultraviolet Free Electron Lasers (UVFELs) and high average power FELs, the former due to the short wavelength and therefore low diffraction, the latter due to large intracavity power. This problem could be solved by inventing more robust mirrors, extending the cavity length, or by using a shorter Rayleigh length, which is the subject of this paper. This method is particularly attractive when the FEL must fit in limited space, such as on a ship. Simple calculations show that one can reduce both the cavity length by half and the power density on the mirrors by more than a factor of two by also reducing the Rayleigh length by a factor of 10 from the conventional value. For example, a 1 MW FEL weapon with wavelength $\lambda = 1\,\mu\mathrm{m}$, dimensionless Rayleigh length $z_0 = 0.2$ and 20 m cavity length has a power density on the mirrors of 1500 kW/cm^2. With $z_0 = 0.02$ and 10 m cavity, power density is reduced to 600 kW/cm^2. In this paper, we study the physics of the FEL interaction while shortening the Rayleigh length in the FEL oscillator, using simulations to visualize the effects. We use the parameters based on the Laser Processing Consortium (LPC) UVFEL [1], but since we use dimensionless parameters the results are widely applicable.

The electric field of a fundamental Gaussian mode is described by [2]

$$a(r,\tau) = \frac{a_0}{w(\tau)} e^{-r^2/w^2 z_0} e^{i\phi(\tau)},$$

where

$$\phi(\tau) = -\tan^{-1}\left[\frac{\tau - \tau_w}{z_0}\right] + \frac{r^2(\tau - \tau_w)}{z_0^2 + (\tau - \tau_w)^2},$$

$$w^2(\tau) = 1 + \left[\frac{\tau - \tau_w}{z_0}\right]^2, \quad z_0 = w_0^2.$$

Transverse dimensions are normalized to $\sqrt{L\lambda/\pi}$. The dimensionless mode radius is given by $w_0 w(\tau)$, where w_0 is the dimensionless mode waist radius and the dimensionless time $\tau = ct/L$, where L is the undulator length. For z_0 small, mode waist is small and the beam rapidly expands towards the end of the undulator. For an electron beam with dimensionless radius $\sigma_e > w_0$, many electrons at the optical mode waist, where the fields are strongest, will not participate in the interaction. Another effect is that of the optical phase shift, as $\tau: 0 \to 1$ for electrons on axis. For example, with $z_0 = 0.1$, $\Delta\phi = 0.9\pi$. This phase shift causes electrons to be resonant only near the undulator center. The shift in phase is smaller for electrons off-axis due to the r^2 term in the expression for ϕ, but as already mentioned, those electrons see weaker fields.

The physics of the FEL interaction in the Gaussian beam thus dictates that one uses an electron beam with a small radius ($\sigma_e < w_0$) and small angular spread (to ensure that electrons are near the axis through the center of the undulator). Thus, optimum electron-beam size in a Gaussian mode is a function of the (constant) dimensionless emittance $\varepsilon = \sigma_e\sqrt{\sigma_\theta}$, where σ_θ is the standard deviation of a Gaussian spread in injection angles [3]. Keeping peak current constant, we vary the electron-beam radius (and therefore angular spread) and reduce z_0 in simulations.

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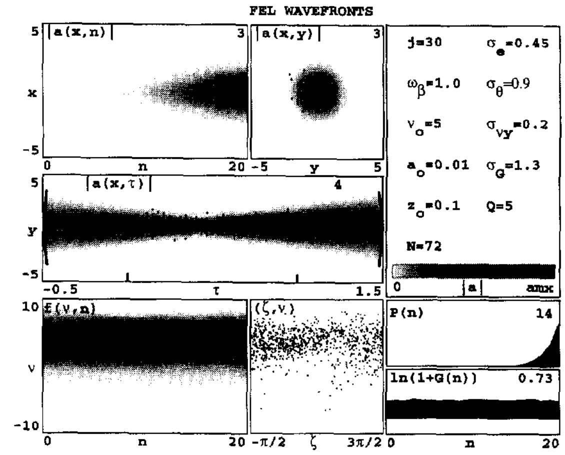

Fig. 1. Three-dimensional simulation of UVFEL showing steady-state gain with $z_0 = 0.1$.

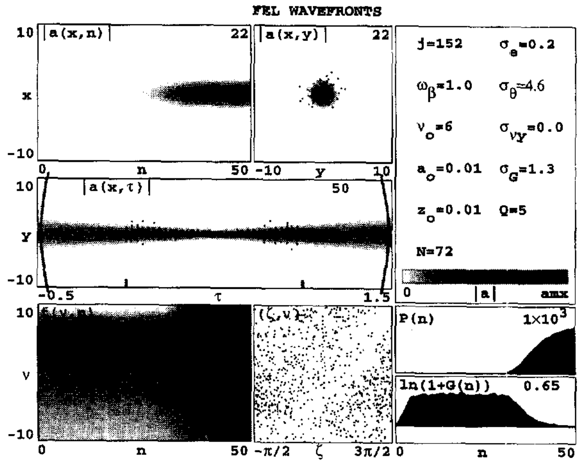

Fig. 3. Three-dimensional simulation of UVFEL showing saturation in strong fields with $z_0 = 0.01$.

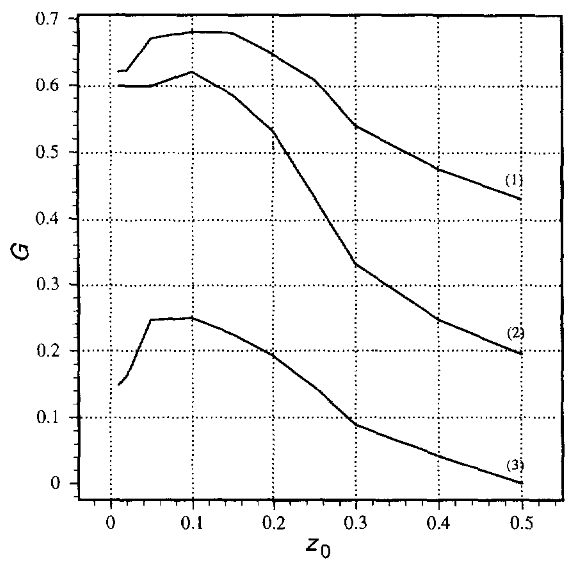

Fig. 2. Plots of steady-state gain versus Rayleigh length for σ_θ = (1) 0.45, (2) 0.2, (3) 0.9.

The three-dimensional (x,y,τ) FEL simulations use the pendulum equation to describe the electrons' motion and the optical wave equation to describe the optical fields [2]. Simulations of a single undulator pass show that gain is reduced as z_0 is reduced from $z_0 = 0.3$ to 0.02 for all sizes of electron beam studied (σ_e = 0.2, 0.45, 0.9, 1.6, with $\varepsilon = 0.43$). Also, the gain evolution $G(\tau)$ departs from exponential for the shortest Rayleigh ranges, showing that electron bunching rate is increased at the undulator center relative to the ends due to the effects discussed above. Reduction of z_0 alone was not sufficient, however, to totally degrade the interaction for any of the electron beam radii used except $\sigma_e = 1.6$, which proved to be too large.

Fig. 1 shows the results of a multiple pass, multimode three-dimensional simulation with $\sigma_e = 0.45$, $\sigma_\theta = 0.9$, $z_0 = 0.1$, and dimensionless current density $j = 30$ [2]. The plot of gain evolution $\ln(1 + G(n))$ at lower right in the figure shows that at $n = 20$ passes,, the oscillator is in the steady-state gain regime in weak fields $|a| \leq \pi$. A sampling of electron positions are drawn over the optical mode in the plots of $|a(x,\tau)|$ and $|a(x,y)|$. The electrons are well inside the optical mode for most of the length of the undulator, which leads to good coupling.

Fig. 2 is a plot of the steady-state gain versus Rayleigh length z_0 for electron beams of radius σ_e = (1) 0.45, (2) 0.2, and (3) 0.9. The figure clearly shows that gain is substantial even at $z_0 = 0.01$, and that optimum gain for the LPC UVFEL is at $z_0 = 0.1$ (see Fig. 1). Note that for $\varepsilon = 0.43$, the electron beam with radius $\sigma_e = 0.45$ (which corresponds to LPC UVFEL parameters) is optimum at any Rayleigh length.

Fig. 3 shows another example of the three-dimensional multimode simulation with $\sigma_e = 0.2$, $\sigma_\theta = 4.6$, $z_0 = 0.01$, and $j = 152$. The plots of electron spectrum $f(v,n)$, final phase space positions (ζ,v), and gain evolution $\ln(1 + G(n))$ show that the oscillator is saturated in strong fields. It is evident from the electron positions drawn over $|a(x,\tau)|$ that the small electron beam radius keeps the electrons near the axis at the undulator center, but the large angular spread moves the electrons outside the mode at the ends.

We have shown that the FEL can achieve substantial gain and saturate in strong fields using Rayleigh lengths as short as $z_0 = 0.01$. The use of a shorter Rayleigh length will reduce mirror power densities and allow for shorter optical cavities in both UV and high average power FELs.

Acknowledgements

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